SOILS, SEC 5 • SOIL AND LANDSCAPE ECOLOGY • RESEARCH ARTICLE

Soil slaking sensitivity as influenced by soil properties in alluvial and residual humid tropical soils

Ronen Francis[1] • Mark N. Wuddivira[2] • Junior Darsan[1] • Matthew Wilson[1,3]

Received: 31 March 2018 / Accepted: 4 November 2018

Responsible editor: Yi Jun Xu

[1]Department of Geography, Faculty of Food and Agriculture, University of the West Indies, St. Augustine, Trinidad and Tobago

[2]Department of Food Production, Faculty of Food and Agriculture, University of the West Indies, St. Augustine, Trinidad and Tobago

[3]College of Science, Geospatial Research Institute, University of Canterbury, Christchurch, New Zealand

✉ Mark N. Wuddivira

mark.wuddivira@sta.uwi.edu

Abstract

Purpose: In the humid Caribbean region characterized by high intensity tropical rainfall, soil aggregate breakdown and pore blocking due to slaking pressures are major land degradation mechanisms. In this research, we investigated the susceptibility of soils to slaking pressures under rapid wetting as influenced by soil properties and the depositional origin from which the soil is formed using water stable aggregates (WSAr) and percolation stability (PSc) as indices of the strength of aggregate inter-particle cohesion.

Materials and methods: Wet sieving and percolation stability analyses were employed to investigate WSAr and pore blocking, respectively. The combined effect of soil properties of clay, organic matter (OM), cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) was used to determine the slaking sensitivity score (SSc) of fourteen physiogeographically important soils in Trinidad, comprising of nine alluvial and five residual soils.

Results and discussion: Results showed that irrespective of alluvial or residual depositional nature of the parent material, samples had high SSc with an average WSAr of 37.8% and PSc of 6.0mm/10 minutes. The linear relationships between SSc with WSAr (r^2 = -0.12) and SSc with PSc (r^2 = -0.012) of all the 14 soils although negative were weak. Clay content accounted for 94.0% of the variation in CEC in alluvial soils and had a strong negative relationships with WSAr (r^2 = -0.74) and PSc (r^2 = -0.79) in residual soils. Additionally, OM with WSAr (r^2 = 0.52) and PSc (r^2 = 0.24), and CEC with WSAr (r^2 = 0.46) and PSc (r^2 = 0.39) showed significant positive linear relationships in residual soil.

Conclusions: The predominantly micaceous and kaolinitic clay mineralogy of these soils coupled with the low OM contents, increase the proneness of the soils to slaking. This suggests

that clay mineralogy is responsible for the high slaking sensitivity rather than clay content or just the depositional origin of the soils. As CEC increases, an accompanying increase in OM is required to increase inter-particle cohesion and to impart partial hydrophobicity, which in turn decreases mineralogically induced susceptibility of individual aggregates to slaking.

Keywords Alluvial parent material • Humid tropical soils • Residual parent material • Slaking sensitivity • Soil aggregates

1 Introduction

Stable soil aggregation of 1-10 mm in diameter (Tisdall and Oades 1982) is vital for adequate permeability, root zone water availability, and to alleviate runoff, erosion and seedling emergence problems associated with breakdown of unstable aggregates (Geeves 1997; Qadir and Schubert 2002; Wuddivira and Camps-Roach 2007). One of the main mechanisms of aggregate breakdown under the intense rainfall of the tropics is slaking (Wuddivira et al. 2013).

Slaking of soil aggregates is the first step in the degradation of soil structure (Wuddivira et al. 2009; Saygın et al. 2012). The slaking process involves the physical break down of soil aggregates into micro-aggregates and finer primary particles by disruptive forces of compressed air entrapped during rewetting or by differential swelling of clays (Wuddivira et al. 2010; Blanco-Moure et al. 2012). For an aggregate to slake, the intrinsic inter-particle cohesive force holding structural units together must succumb to the disruptive forces of pressure build-up due to entrapped air exerted in macro-pores during rapid wetting (Grant and Dexter 1990; Zaher et al. 2005). Emerson (1977) opined that soils dominated by clay minerals such as kaolinite and illite slake more extensively due to compressing of entrapped air while montmorillonitic soils slake due to differential swelling. Hence, soil slaking reduces the ability of the soil to optimally carry out its agricultural, environmental and hydrological functions.

Socioeconomic-driven anthropogenic practices such as conversion of forest to crop lands, slash and burn agriculture and conventional tillage operations, expose the soil surface to the direct impact of intense tropical rainfall, thereby increasing the susceptibility of soil aggregates to aggregate breakdown due to slaking pressures (Almajmaie et al. 2017). Also, these practices promote soil organic matter loss (Arouays and Pelissier 1994), as well as soil structure deterioration and alter hydrological regime of catchments (Sahani and Behera 2001; Osman 2014). Consequently, aggregate breakdown due to slaking is of particular importance in the humid tropics with marked dry periods followed by high intensity rainfall (Wuddivira et al. 2009).

Previous studies focused on the soil factors which influence aggregate slaking by rapid wetting (Wuddivira et al. 2009; Wuddivira et al. 2010; Almajmaie et al. 2017). Almajmaie et al. (2017) demonstrated that these soil factors are mostly inherent soil properties such as texture and clay mineral content. In addition, soil properties are reflective of the parent material from which the soil is formed (Douglas 1988; Heung et al. 2014). Parent material and texture are therefore recognized as useful factors in soil erosion and degradation (le Roux et al. 2007; Heung et al. 2013). Chesworth (1973) highlighted that it is almost impossible to determine the parent material of a soil if not found in place as residuum, therefore, it would only be in young soils that parent material exerts its strongest effect on soil factors, which is eventually nullified with time. Nonetheless, studies have shown that nullification time varies and it may take millions of years before two adjacent soils are indistinguishable. Concomitantly, in young soils as in the Caribbean (Ahmad 2011), parent material strongly influences soil factors and thus the slaking sensitivity of soils.

Soil factors, wetting rate and antecedent moisture content have been shown to control aggregate slaking (Marques et al. 2004; Wuddivira et al. 2010). Since slaking was assumed to occur only under rapid wetting of dry aggregates, wetting rates and antecedent moisture contents are constants and soil factors are the only dynamic variables that influence the slaking process (Fig. 1). Hence, in the study conducted by Wuddivira et al. (2010), the soil factors were classified and ranked in order of their importance on the slaking process with clay content ranked as the most important, followed by organic matter content (OM), then exchangeable sodium percentage (ESP) and cation exchange capacity (CEC). Soil aggregate sensitivity to slaking pressures therefore depends on the compositional combination of the soil factors in the aggregate.

Soil aggregate stability and organic matter are critical indicators of soil quality and environmental sustainability (Paul et al. 2013; Atwell et al. 2018). They are important in increasing the resistance of aggregates to slaking pressures. Consequently, WSAr has been used as an index of the cohesive force holding particles together within aggregates (Wuddivira et al. 2013). Another useful index is PSc (Mbagwu and Auerswald 1999, Guedes Filho et al. 2013) that measures the infiltration of water through a soil as an indication of the resistance or susceptibility of dry aggregates to the disruptive effects of pressure build-up of entrapped air during rapid wetting (Auerswald 1995).

Aggregate stability has been known to correlate strongly with organic matter (Chancey and Swift 1984; Alagöz and Yilmaz 2009). OM acts as a binding agent via organic polymers (Chenu

2000; Abiven et al. 2009) and imparts partial hydrophobicity by coating aggregates and occludes pores sensitive to slaking (Zaher et al. 2005). CEC also acts as a stabilizing agent in soil aggregates (Robinson and Page 1950; Schroeder 1984). Ruiz-Vera (2006) found that high sodium levels in soil increase crusting and swelling. High sodium levels also diminish water flow, aeration and reduce the capacity of the soil to support plant growth.

Although the study by Wuddivira et al. (2010) provides some insights on the effect of soil factors on slaking sensitivity of humid tropical soils of the Caribbean, the soil factor ranking model developed in their study had a number of limitations. We conclude that the limitations are due to the scant systematic understanding of the effect of the parent material from which the soil factors emanate on the slaking sensitivity of soils. Thus, the depositional characteristics of the soil parent material as residuum or alluvium influences the soil factors and slaking sensitivity. The objectives of the study were i) to evaluate slaking sensitivity as influenced by the alluvial and residual nature of soils, and ii) to investigate the effects of soil properties on the slaking sensitivity of alluvial and residual humid tropical soils.

2 Material and methods

2.1 Physiography of the study area

Trinidad and Tobago is an archipelagic state consisting of two main islands found 11Km from the north-east coast of Venezuela. The study was conducted in Trinidad, the largest of the two islands, occupying an area approximately 4,827 km^2 and located 100 2’ and 110 12’ north latitude, and 600 30’ and 610 56’ west longitude. The closeness of Trinidad to the equator allows it to have a tropical maritime climate marked with a distinct dry period between January to May and a moist equatorial climate from June to December which encompasses the hurricane season (Trinidad and Tobago meteorological services 2017). The moist equatorial climate is also often interrupted by short dry periods referred to as the petit carême (Gumbs 1982). Rainfall is about 2,000mm annually and evapotranspiration is about 60 percent of the rainfall received (Tambie et al 2012). Climate variability is high in Trinidad due to El Nino Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). The tropical landscape and mountainous topography influences various microclimates and the country hosts many ecosystems including Ever-green and Semi Ever-green seasonal forests, deciduous seasonal forest, littoral woodlands and savannas (Beard 1946; Trinidad and Tobago meteorological services 2017). Sindelar (2015) indicated that soils developing under these ecosystems would be deep and well developed, however, the youthful geological nature of Trinidad, results in mostly young undeveloped soils (Ahmad 2011).

The soils were taken from the Northern plain and the Northern range (Fig. 2). The Northern plain consists of a low-lying belt of land which extends from the south facing catena of the Northern range. The land is slightly elevated in the centre with extensive terraces flanking the south face of the Northern range and the north face of the Central range (Sutton 1955). All areas are drained by rivers extending to the south from the Northern range and merging with the Caroni River to empty on the west coasts from the centre of the island (Fig. 2). The major Caroni River empties into the Caroni coastal swamp at the Gulf of Paria. The soils are classified based on the USDA Soil Taxonomy 12th edition (2014).

2.2 Soil sampling, preparation and analysis

Using GIS technology, the soil attributes and land cover characteristics of the sample areas were surveyed. ArcGIS was used to query soil shape files to produce a suitable overlay to include land use and vegetation cover, elevation and soil series. Simple random sample points were generated within a WGS 1984 UTM Zone 20N mapping grid over Trinidad with parameters; latitude (100 0’0” N – 100 50’0” N) and longitude (600 55’0” W – 610 60’0”W). Only points above 100 30’ 0” N, in the north that fit the query criteria were considered for this evaluation of soil slaking. The sample sites must have land cover equalling any natural vegetation type except swamps and wetlands. Elevation had to be at least 1m above sea level and the soil series (Table 1) were preselected from a population of 23 ecologically and agriculturally important soils in Trinidad evaluated by Wuddivira et al (2010). The first two generated points which appeared in a database file for each of the selected alluvial soil series after running the query were taken as sample locations. The residual samples were selected from the unclassified soil series in five mountain locations of the Northern Range in Maracas St Joseph, Mt St Benedict, Caura, D’Abadie and Blanchisseuse. Four samples were collected at each location at 10 m intervals along a tape laid out in a downslope position. At each sampling site, disturbed soil samples were collected at 15cm depth using a soil auger. Soils were air dried and sieved through a 2 mm mesh. Residual and alluvial soils were assigned (R) and (A) respectively after their series names.

Soil texture was determined using the hydrometer method (Gee and Or, 2002). Soil pH was measured in a 1:2.5 soil/water ratio after being left to equilibrate for 30 minutes and stirred intermittently. Soil organic matter content was determined by oxidation of organic carbon using Walkley-Black procedure (Nelson and Sommers 1982). The CEC of the acid soils was determined using the un-buffered salt extraction method (Rhoades 1982) while ammonium acetate buffered method was used for calcareous soils (Rhoades 1982).

2.3 Aggregate stability

Water stable aggregates under rapid wetting (WSAr) of the samples were measured using a method described by Angers et al. (2008) and modified by Wuddivira et al. (2009). The method used a single sieve wet sieving apparatus with a stroke of 1.3 cm and a frequency of about 34 cycles min^{-1} (Eijkelkamp Agrisearch Equipment, Giesbeek, NL). Before wet sieving, four grams of 1 to 2 mm air dried aggregates were placed in 0.25 mm meshed sieves in the wet sieving apparatus and abruptly immersed for 10 mins in weighed labelled cans containing deionized water. This was done to induce slaking pressures on the aggregates mimicking natural conditions when dry soil aggregates are rapidly wetted under intense rainfall (Wuddivira et al. 2009). This was then followed by wet sieving for 15 mins and allowed to drain completely. After draining, the cans now containing the unstable aggregates (<0.25 mm) were removed and placed on a tray. The aggregates that remained in the sieve after wet sieving (stable aggregates >0.25 mm), were then dispersed in a second set of weighed labelled cans containing 0.02 mol L^{-1} sodium hexametaphosphate for soils with pH >7 or with 0.02 mol L^{-1} NaOH for soils with pH< 7. Both sets of cans were oven dried at 105°C for 24 hours. The percentage WSAr (sand-free basis) of the soils was then calculated as being the ratio of the mass of the stable aggregates (Ms) divided by the summation of the mass of the stable aggregates plus unstable aggregates (Mu) as in equation 1:

$$WSA_r = (Ms / M_s + M_u) \times 100 \qquad (1)$$

2.4 Percolation stability

Percolation stability of the soils was measured on the calibrated air-dried aggregates of 1-2mm size as described by Wuddivira (2008). A muslin cloth and 1-2 mm of cotton wool to maintain an atmospheric pressure and free movement of air and water, were placed at the the bottom of a cylindrical, plexiglas tubes 3cm in diameter and 10cm long. The tube was homogeneously packed with the aggregates by mechanically dropping the tube 10 times from a height of 2 cm onto a hard surface of a workbench leaving a head space for ponding of water. A grade 40 (8 μm pore size) Whatman filter paper was placed on top of the aggregates to prevent surface structural deterioration by direct impact of water on the aggregates but deterioration occured only by slaking forces. The tube was then placed on a holder and deionize water was used to percolate the aggregate column under a hydrostatic pressure head of 20 kPa using a mariotte bottle. The amount of water that percolated in 10 minutes through the soil column was collected and was regarded as the uncorrected percolation stability. Percolation stability is positively influenced by the sand content of the soil, which does not imply increase in stability (Mbagwu and Auerswald 1999). The measured percolation stability was corrected for total sand in the aggregate as follows (Mbagwu and Auerswald 1999):

$$PSc = \frac{PSu \times (100 - \%Sand)}{100} \quad (2)$$

where PSc is percolation stability with sand correction (cm^3/10 minutes); PSu is percolation stability without sand correction (cm^3/10 minutes). The depth of water percolated in 10 minutes is given by:

$$PSc = \frac{Vp}{Ac} \quad (3)$$

where Vp is Volume of water percolated in 10 minutes after sand correction; Ac is cross-sectional area of the column.

2.5 Applied model

The previously developed slaking sensitivity ranking framework by Wuddivira et al. (2010) was used to assess the slaking sensitivity score of residual as well as alluvial soils. The slaking sensitivity ranking model is in the form:

$$SSc = \sum_{i=1}^{n} fili \qquad (4)$$

where SSc is the soil slaking sensitivity score, n is the number of factors, fi is the ith ranked factor score based on the influence of the factor on soil slaking sensitivity and li is the ith level of the factor's influence on slaking sensitivity.

Based on the model, the contribution of each soil factor of clay, OM, ESP and CEC referred to as factor rank (FR) at a particular concentration level of the factor referred to as level rank (LR) on SS is a product of factor rank (FR) and level rank (LR).

$$SS = FR \times LR \qquad (5)$$

3 Results

3.1 Particle size distribution and aggregate stability indices

The textural classes of the soils are presented in Table 2. Oropuna (A), the only heavy textured soil series had the largest clay content of 68.2%. Cunupia (A) classified as Silty Clay, had the smallest sand (2.5%) with a fine fraction (silt + clay) of 97.5%. Tacarigua (A) series was a Silt Loam with the largest silt content (56.1%). Most of the 14 soils had fine fraction content of between 50-85%. Only in Cleaver (A) and Maracas (R) did the sand fraction exceed 50%.

The WSAr and PSc of the 14 soil series are shown in Table 2. Streatham (A) (WSAr =12.3%; PSc = 0.62 mm/10min) and Cleaver (A) (WSAr=63.7%; PSc = 13.2 mm/10min) represented the smallest and largest WSAr and PSc for alluvial soils, respectively. Blanchisseuse (R) (WSAr=25.3%; PSc =2.6mm/10min) and Mt St Benedict (R) (WSAr=57.7%; PSc = 11.8mm/min) had the smallest and largest WSAr for residual soils, respectively. The mean WSAr amongst the soils was 37.8%. Three additional soils; Maracas (R), St Augustine (A) and Anglais (A) with WSAr 44.2%, 54.4% and 59.8%, respectively had WSAr greater than the mean value. Mean PSc was 6.0mm/10min; Mt St Benedict (R), Maracas (R), Cleaver (A), Anglais (A), St Augustine (A) and Cunupia (A) were all greater than the mean.

3.2 Relationship between aggregate stability indices and soil properties

Increasing clay content does not always result in an increase in aggregate stability as highly expansive clays can increase entrapped air and result in diminished aggregate stability under rapid wetting (Lado et al. 2004; Wuddivira et al. 2009). Wuddivira et al. (2009) showed that there is a threshold clay content below which slaking of soil aggregates increased regardless of organic matter content and beyond which an accompanying increase in OM is required to expand the structural stabilizing role of clay. The fourteen soils showed a weak negative linear relationship between WSAr with clay content (r^2 = -0.12) and between PSc with clay content (r^2 = -0.16). However, the linear relationship between WSAr with PSc was strong and positive (r^2=0.72), indicating that both indices measure inter-particle aggregate cohesion and the susceptibility of aggregates to slaking pressures of rapid wetting. Further examination of the influence of clay within alluvial and residual categories, the strength of the relationship varied greatly. Poor relationship (r^2 =0.05 and r^2 = -0.06) existed between WSAr and PSc with clay content in alluvial soils while in residual soils, there was a strong negative relationship (r^2 = -0.74 and r^2 = -0.79) between WSAr and PSc with clay content (Fig. 3). Considering the soil factors (Table 2), the greatest clay content (68.2%) and CEC (9.5 cmol/kg) of Oropuna (A) did not translate into the greatest WSAr as would have been expected, which partly explains the negative relationship.

The relationship between WSAr and OM was also critical in the water stability of aggregates, however; only in residual soils was this relationship significant. Mt St Benedict (R) had the greatest OM (4.4%) and yielded one of the highest WSAr (57.7%), although its clay content was low. The relationship between WSAr and OM for the 14 soils was weak but positive (r^2 =0.14). Comparatively, the r^2 decreased to 0.07 in alluvial soils while it increased to 0.52 in residual soils at a 95% confidence interval. PSc did not show any relationship with OM in the 14 soils, nor when categorized based on depositional origin.

River Estate (A) soil series reflected a combination of soil factors which would had the most negative effect on its WSAr (16.6%) based on the slaking sensitivity ranking framework by Wuddivira et al, (2010). The soil had ESP (3.7%), OM (0.7%), Clay (14.4%) and CEC (2.3 cmol/kg). Only Streatham (A) had a lower WSAr (12.3%), although its CEC, clay content and OM were greater than that of River estate (A). ESP had a weak negative relationship with WSAr of less than r^2 = 0.25 for all the soil groupings (Table 3). Cation exchange capacity was not significantly related to WSAr when examining the 14 soils or the 9 alluvial soils. There was, however, a moderate relationship between CEC and WSAr (r^2 = 0.48) in residual soils. Multiple regression analysis with clay content, OM, CEC and ESP showed that only 32.8 % of the variation in WSAr was explained by these soil factors. However, the F statistic (2.585) was not significant (P = 0.109), suggesting that the predictive model had no explanatory power.

3.3 Assessing the slaking sensitivity of the soils

The slaking sensitivity model developed by Wuddivira et al. (2010) was applied to determine the slaking sensitivity of the soils based on the origins of their parent material as alluvial or residual. All the 14 soils were classified as “high slaking” soils. Their slaking sensitivity scores were greater than 20 (Table 4). A high slaking sensitivity score of 22 was shared by Oropuna (A) and Mt St Benedict (R) with River Estate series having the highest slaking sensitivity score of 27. The maximum SSc measured for CEC was 12 for all fourteen soils while OM has a maximum SSc value of 6 for all soils except Mt St Benedict (R) with a score of 4. Clay content and ESP varied widely across the fourteen soils. Chi square analysis indicated that there was a significant difference in the WSAr and SSc between the nine alluvial soils assessed in this investigation and nine similar soils examined by Wuddivira et al, (2010). Nevertheless, “high slaking” classes were recorded for both sets of soil except for Anglais and Cunupia which were reported as “medium slaking” by (Wuddivira et al., 2010).

The relationship between WSAr and SSc is presented in Fig. 4. There was a weak negative relationship (r^2 = -0.13) between WSAr and SSc.

4 Discussion

4.1 Influence of soil properties on aggregate stability

Aggregate stability by rapid wetting (WSAr) and Percolation stability (PSc) in residual soils had a strong negative linear relationship with clay percentage. This indicates that as the clay content increases, slaking increases in residual soils. Hence, the finer particles generated block water conducting pores thereby slowing water conductivity. Wuddivira et al. (2009) and Wuddivira et al. (2013) reported that in tropical soils of Trinidad, medium (20–45% clay) and high clay (>45%) soils slake as much as low clay (<20% clay) soils under rapid wetting when organic matter content is low (<3%). However, the resistance to slaking pressures increased at medium and high clay contents when organic matter content is high (>3%). The authors therefore concluded that a clay content threshold exists at the medium clay category below which soils succumb to slaking pressures and above which high organic matter is required to reduce the surface tension of water entering the clay–organic matter matrix and thus increasing the cohesion of the clay particles. Except for Mt. St. Benedict (R) which was low in clay (14.2%) and high in OM (4.4%), the rest of the residual soils fall into medium clay category with critically low OM content (<1.6%). Also, the residual soils were sampled in the upland regions of the Northern Range of the southern catenae landscapes that extend into the Northern Basin, dominated by kaolin and illitic clays with mineralogical constituents of mostly pyrites, sericite, chlorite, quartz and feldspar (Brown et al. 1965; Ahmad 2011). Hence at the medium clay range, the illitic mineralogy, which increases soil proneness to swelling upon wetting (Piccolo et al. 1997; Singer et al. 1992), causes the slaking pressures to overcome the already weak cohesive bonds characterized by low OM. This indicates that the WSAr and PSc of the residual soils depend on the clay mineralogy of the soils. In the alluvial soils of the terraces, which are derived from the parent material washed down by the northern rivers into the flood plains, the relationship between the clay and WSAr was poor (r^2 = -0.05). This is an indication that other soil fractions besides clay (Chenu 2000), may be contributing to the WSAr. Sand was slightly more correlated to WSAr with an improved positive r^2 of 0.15 than clay.

Chenu et al. (2000) found a strong linear relationship between WSAr and soil organic matter (SOM) ($r^2 = 0.71$) in loamy soils of southwest France. SOM has also shown to decrease aggregate wettability thereby promoting the formation and protection of stable aggregates (Goebel 2005; Wuddivira et al. 2013). Seven of the nine alluvial soils examined excluding Cunupia and Oropuna had textures in the loam range (Table 2). The OM in these soils, however, did not result in a significant relationship ($r^2 = 0.07$) with WSAr. This small variation in WSAr induced by OM can be attributed to the narrow range of OM content in the alluvial soils (OM 0.5- 1.8 %), all of which fall within the low OM range (Wuddivira et al. 2009). A previous study including these alluvial soils showed a broader range of OM contents (low contents of 1.4 to high contents of 5.1%) and yielded a strong linear regression between OM and WSAr (Wuddivira et al. 2010). Several authors such as Wallis and Horne (1992), Zaher et al. (2005), and Wuddivira et al. (2013), indicated that organic matter imparts partial hydrophobicity by adding hydrophobic coatings to individual aggregates. This slows the entrance of water into intra-aggregate pore spaces, thus increasing internal cohesion and reducing aggregate susceptibility to slaking.

The OM in the residual soils showed a stronger relationship with WSAr ($r^2 = 0.52$). The OM (4.4%) for Mt St Benedict (R) was more than twice as high as in the other soils. The teak forest vegetation from where Mt St Benedict (R) series was collected coupled with the regularity of forest fires in the area, allowed the build-up of organic matter in the soil. Mt St Benedict (R) also had the highest aggregate stability among residual soils, which is attributable to the aggregate stabilizing effect of organic matter. Considering the 14 soils, organic matter was a relatively poor contributor to the variation in WSAr, due likely to its generally low content and narrow range in the soils. Organic matter data showed that 13 of the 14 soils had less than 2%

organic matter content. Despite the low OM of Cleaver (A) 1.7% and Anglais (A) 0.9%, their high WSAr percentages of 63.7% and 59.8% respectively, indicate the influence of factors other than OM on the aggregate stability of these soils.

The CEC of soils vary based on clay minerals and organic matter contents. Mendoca and Rowell (1996) indicated that 2:1 clays, especially smectites with negatively charged sites, are predominantly responsible for high CEC. Thus, a reduction in these types of clays leads to a greater importance of organic matter as a major contributor to soil CEC. The soils in the Northern Range of Trinidad are predominated by 1:1 kaolinitic clay minerals and 2:1 fine grain micas (Brown et al. 1965; Ahmad 2011), which are easily weathered and leached of cations. In the residual soils collected from upland regions, there was a negative relationship between clay and CEC ($y = -0.0836x + 5.0767$) where clay accounted for 66.9% of the variation in CEC. This would have limited the potential of CEC and clay to increase aggregate stability based on the theory of the slaking sensitivity ranking framework (Wuddivira et al. 2010). Nevertheless, CEC still positively accounted for 45.5% of the variation in WSAr. Further, it can be inferred that the occurrence of high WSAr percentages was due to moderate to low ESP levels (1.1% -3.5%) in the residual soil where ESP is ranked as a more important soil factor predictor in aggregate slaking than CEC.

In the alluvial soils, 1:1 clays such as Kaolinite were dominant (Table 1) and clay content accounted for 91.2% of the variation in CEC. In addition to this, the organic matter content of these soils was very low and Wuddivira et al. (2010) indicated that where organic matter is not a major contributor of CEC, aggregate stability and CEC is essentially determined by clay mineralogy.

4.2 Slaking in residual and alluvial soils

Since the parent material from which a soil is formed influences soil properties, which in turn affects the sensitivity of soil aggregates to slaking, the slaking sensitivity ranking model (Wuddivira et al. 2010) was applied to discriminate the slaking of residual and alluvial soils. Based on the model, there were no notable differences in slaking sensitivity due to the parent material origin of the soil. The residual soils fall under the same class of high slaking sensitivity as the alluvial soils. The residual soils were expected to be more resistant to slaking than the alluvial soils due to their in situ development; however, they were as sensitive as the alluvial soils. The high slaking sensitivity of the soils was due to low CEC attributable to the low organic matter content and clay mineralogical, which was predominantly kaolinitic. The CEC and clay mineralogy relationship can be considered the most prominent because of the great influence clay mineralogy has on isomorphic substitutions and the retention of cations. Sombroek (1966), while investigating Amazonia soils, discovered that kaolinite was highly weathered and its ability to retain cations was due to organic matter content. In the case of these Northern Range residual soils, organic matter content was low, thus, none of the three aggregate stability promoting soil factors (Clay content, OM and CEC) were effective in alleviating slaking sensitivity.

5 Conclusions

We examined water stable aggregates (WSAr) and percolation stability (PSc) as indices of the strength of aggregate inter-particle cohesion under rapid wetting influenced by soil properties and the depositional origin of soils. The strong linear relationship between WSAr with PSc suggests that both are indicators of the aggregate cohesion and thus the susceptibility of aggregates to slaking pressures of rapid wetting. Although cohesive property of clay had a weak linear relationship with WSAr and PSc, the negative relationship indicates the tendency of clay content to increase slaking. The dominant 2:1 fine grain micas and kaolinitic clay mineralogy of these soils undermined the cohesive property of clay under rapid wetting and increases their proneness to slaking, particularly as the cohesive property of organic matter content was low. Organic matter at such a low level could not decrease the surface tension of water entering the clay–organic matter matrix and thus weakening the cohesion of the clay particles. In spite of the fact that the relationship between OM with WSAr (r^2 = -0.07) and PSc (r^2 = -0.05) was weak in alluvial soils, the relationship was stronger (OM vs WSAr, r^2 = 0.52) in residual soils, even so, both soil groups were highly sensitive to slaking.

Clay minerals and organic matter are major contributors to CEC in soils. Both the residual and alluvial soils are dominated by 1:1 kaolinitic clay minerals and 2:1 fine grain micas, which are easily weathered and leached of cations. In residual and alluvial soils, clay negatively accounted for 66.9% and 91.2% of the variation in CEC, respectively. However, since organic matter content of these soils was very low, OM was not a major contributor of CEC, hence aggregate stability and slaking sensitivity of these soils were essentially determined by clay mineralogy. Therefore, clay mineralogy rather than clay content or the depositional origin of the soils is responsible for the high slaking sensitivity of the soils.

References

Agbu PA, Jones RL, Ahmad N (1990) Mineralogy and weathering of a Trinidad Ultisol developed in porcellanite. Soil Sci 149:272–278

Ahmed N (2011) Soils of the Caribbean. Ian Randle Publishers

Ahmad N, Breckner E (1974) Soil erosion on three Tobago soils. Trop Agri 51:313–324

Almajmaie A, Hardie M, Doyle R, Birch C, Acuna T (2017) Influence of soil properties on the aggregate stability of cultivated sandy clay loams. J Soils Sediments 17:800-809

Angers DA, Bullock MS, Mehuys GR (2008) Aggregate stability to water. In: Carter MR, Gregerich EG (eds) Soil Sampling and Methods of Analysis. 2nd ed, Florida. CRC Press, pp 811-818

Angers DA, Mehuis GR (1989) Effects of cropping on carbohydrates content and water stable aggregation of clay soil. Can J Soil Sci 69:373-380

Arrouays D, Pelissier P (1994) Changes in carbon storage in temperate humic loamy soils after forest clearing and continuous corn cropping in France. Plant Sci 160: 215-223

Auerswald K (1995) Percolation stability of aggregates from arable topsoils. Soil Science 159:142-148

Atwell MA, Wuddivira MN, Wilson M (2018) Sustainable management of tropical small island ecosystems for the optimization of soil natural capital and ecosystem services: a case of a Caribbean soil ecosystem—Aripo savannas Trinidad. J Soils Sediments 18:1654-67

Beldin SI, Caldwell BA, Sollins P, Sulzman EW, Lajtha K, Crow SE (2007) Cation exchange capacity of density fractions from paired conifer/grassland soils. Biol Fert Soils 43:837-841

Bieganowski A, Ryzak, M, Witkowska-Walczak B (2010) Determining soil aggregate disintegration dynamics using laser diffraction. Clay Min 45:23-34

Blanco-Moure N, Moret-Fernández D, López MV (2012) Dynamics of aggregate destabilization by water in soils under long-term conservation tillage in semiarid Spain. Catena 99:34-41

Bohn LH, McNeal LB, O'Connor AG (1979) Soil Chemistry. New York, John Wiley and Sons Ltd

Chaney K, Swift RS (1984) The influence of organic matter on aggregate stability in some British soils. J Soil Sci 35:223-230

Chesworth W (1973) The parent material effect in the genesis of soil. Geoderma 10:215-225

Chenu C, Le Bissonnais Y, Arronayas D (2000) Organic matter influence on clay wettability and soil aggregate stability. Soil Sci Soc Am J 64:1479-1486

Collins-George N, Lal R (1971) Infiltration and structural changes as influenced by initial moisture content. Aust J Soil Res 9:107-116

Dell'Aquila R (2007) Automatic sieve-shaker for determining aggregate stability and dimensional distribution using a vertical oscillation system. Ital J Agron 4:401-406

Dormaar JR (1983) Chemical properties of soil and water-stable aggregation after sixteen years of cropping to spring wheat. Plant Sci 75: 51-61

Douglas WA, Lietzke DA, Zelazny LW (1988) Effect of parent material weathering on chemical and mineralogical properties of selected hapludults in the Virginia Piedmont. Soil Sci Soc Am J 52:196-204

Downe RG, Leeper GW (1939) The Measurement of Soil Structures. Proc Roy Vic Soc 52:1-20

Ehrlich WA, Rice HM, Ellis JH (1955) Influence of the composition of parent materials on soil formation in Manitoba. Can J Agr Sci 35:407-421

Emerson W (1977) Soil factors in crop production in a semi-arid environments. In: Russell JS, Greacen EL (eds) Physical Properties and Structures, Australia. University of Queensland Press, 78-104

Grant CD, Dexter AR (1990) Air entrapment and differential swelling as factors in the mellowing of moulded soils during rapid wetting. Aust J Soil Res 28:361–369

Guedes Filho O, da Silva AP, Giarola NFB, Tormena CA (2013) Structural properties of soil seedbed submitted to mechanical and biological chiselling under no-tillage. Geoderma 204-205: 94-101

Gumbs FA (1982) Soil and Water management features in Trinidad and Guyana. Trop Agri 59:76-81

Hamblin AP (1980) Changes in aggregate stability and associated organic matter properties after direct drilling and ploughing on some Australian soils. Aust J Soil Sci 18: 27-36

Hanson DL, Steenhuis TS, Walter MF, Boll J (2004) Effects of soil degradation and management practices on the surface water dynamics in the Talgua river watershed in Honduras. Land Degrad Dev 15:367–381

Heung B, Bakker L, Schmidt MG, Dragićević S (2013) Modelling the dynamics of soil redistribution induced by sheet erosion using the Universal Soil Loss Equation and cellular automata. Geoderma 202–203:112–125

Heung B, Bulmer CE, Schmidt M.G (2014) Predictive soil parent material mapping at a regional-scale: a random forest approach. Geoderma 214:141-154

Iruak S, Surucu AK, Aydogdu IH (2007) Effects of different parent material on the mineral characteristics of soils in the arid region of Turkey. Pak J Biol Sci 10:528-536

Jenny H (1941) Factors affecting soil formation: A system of quantitative pedology. New York, McGraw-Hill Book Company, Inc.

Kemper WD, Chepil WS (1965) Size distribution of aggregates. In: Black CA (eds) Methods of soil Analysis, Part 1. 1st edition USA American society of Agronomy Education, pp 499-510

King LC (1962) The morphology of the earth. Edin Geo Soc 19:669-675

Kugler HG (1959) Explanatory notes for geological map of Trinidad

Lado M, Ben-Hur M, Shainberg I (2004) Soil wetting and texture effects on aggregate stability, seal formation, erosion. Soil Sci Soc Am J 68:1992-1999

Lal R (1996) Deforestation and land use effects on soil degradation and rehabilitation in western Nigeria 1. Soil physical and hydrological properties. Land Degrad Dev 7:19-45

le Roux JJ, Newby TS, Sumner PD (2007). Monitoring soil erosion in South Africa at a regional scale: review and recommendations. S Afr J Sci 103:329–335

Liang B, Lehmann J, Solomon D, Kinyanhi J, Grossman J, O’Neell B, Skjemstad OJ, Thies J, Luizao FJ, Petersen J, Neves EG (2006) Black carbon increases cation exchange capacity in soils. Soil Sci Soc Am J 70:1719-1730

Marquez CO, Garcia VJ, Caimbardella CA, Schultz RC, Isenhart TM (2004) Aggregate-size stability distribution and soil stability. Soil Sci Soc Am J 66:725-735

Mbagwu JSC, Auerswald K (1999) Relationship of percolation stability of soil aggregates to land use, selected properties, structural indices and simulated rainfall erosion. Soil Til Res 50:197-206

Mendoca ES, Rowell DL (1996) Mineral and organic fractions of oxisols and their influene on effective cation exchange capacity. Soil Sci Soc Am J 60:1888-1892

Nelson DW, Sommers LE (1982) Total Carbon, Organic Carbon, and Organic Matter. In Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties edited by Page AL, Miller RH, Keeney DR, Madison WI. Soil Sci Soc Am, Inc., pp 539-579

Osman KT (2014) Physical Deterioration of Soil. In: Soil Degradation, Conservation and Remediation. Springer Netherlands, pp 45-67

Peinemann N, Amiottie MN, Zalba P, Villamil MB (2000) Effects of clay minerals and organic matter on the cation exchange capacity of silt fractions. J Plant Nutr Soil Sci 163:47-52

Pennock D, Yates T, Braidek J (2008) Soil Sampling Design water. In: Carter MR, Gregerich EG (eds) Soil Sampling and Methods of Analysis. 2nd ed, Florida. CRC Press, pp 722-731

Piccolo T, Pietramellara G, Mbagwu JSC (1997) Use of humic substances as soil conditioners to increase aggregate stability. Geoderma 75:267-277

Plaster RW, Sherwood WC (1971) Bedrock weathering and residual soil formation in central Virgina. Geol Soc Am 82:2813-2826

Robinson DO, Page JB (1950) Soil aggregate stability. Proc Soil Sci Soc Am 15:25-29

Rhoades JD (1982) Cation Exchange Capacity. In: Page AL, Miller RH, Keeney DR, Madison WI (eds) Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. Soil Sci Soc Am, Inc., pp 149-157

Ruiz-Vera VM, Wu L (2006) Influence of sodicity, clay mineralogy, pre-wetting rate, and their interaction on aggregate stability. Soil Sci Soc Am J 70:1825–1833

Saygın SD, Cornelis WM, Erpul G, Gabriels D (2012) Comparison of different aggregate stability approaches for loamy sand soils. Appl Soil eEcol 54:1-6

Sahani U, Behera N (2001) Impact of deforestation on soil physicochemical characteristics, microbial biomass and microbial activity of tropical soil. Land Degrad Dev 12:93-105

Schaetzl R, Anderson S (2005) Soil Gneiss and Geomorphology. New York, Cambridge Press

Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA (2011) Persistence of soil organic matter as an ecosystem property. Nature. 478:49-56

Schroeder D (1984) Soils: Facts and Concepts. Switzerland, International Potash Institute

Sindelar M (2015) Soil and Climate. Soil Science Society of America, Retrieved from www.soils.org/IYS on 12th June 2017

Singer MJ, Southard RJ, Warrington DJ, Janitzky P (1992) Stability of synthetic sand clay aggregates after wetting and drying cycles. Soil Sci Soc Am J 56:1843-1848

Sombrock WG (1966) Amazon Soils: A reconnaissance of the soils of the Brazilian Amazon Region, Wageningen. Wageningen Centre for Agricultural Publications and Documentation

Stephen I (1952) A study of rock weathering with reference to the soils of the Malvern hills; weathering of biotite and granite. J Soil Sci 3:20-33

Sutton AGA (1952) Report on the General Geology of Trinidad

Talibudeen O (1981) Cation exchange in soils. In: Greenland DJ, Hayes MH (eds) The Chemistry of Soil Processes. New York, John Wiley and Sons Ltd

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33:141-163

van Dijk AIJM, Meesters AGCA, Bruijnzeel LA (2002) Exponential distribution theory and the interpretation of splash detachment and transport experiments. Soil Sci Soc Am J 66:1466–1474

Wall GP, Sawkins JG, Etheridge R, Cruger H (1860) Report on the geology of Trinidad: Part I of the West Indian Survey. Geological Survey of Great Britain. London, Longman

Wallis MG, Horne DJ (1992) Soil water repellency. In: Stewart BA (ed) Advances in Soil Science, 20. New York, Springer-Verlag, pp 91-146

Wuddivira MN (2008) Structural stability, hydraulic properties and erodibility of humid tropical soils under intense rainfall, PhD Thesis. The University of the West Indies, St. Augustine, Trinidad and Tobago, West Indies

Wuddivira MN, Ekwue EI, Stone RJ (2009) Clay, Organic Matter, and Wetting Effects on Splash Detachment and Aggregate Breakdown under Intense Rainfall. Soil Sci Soc Am J 73:226-232

Wuddivira MN, Ekwue EI, Stone RJ (2010) Modelling slaking sensitivity to assess the degradation potential of humid tropic soils under intense rainfall. Land Degrad Dev 21:61-73

Wuddivira MN, Ekwue EI, Stone RJ (2013) Influence of cohesive and disruptive forces on strength and erodibility of tropical soils. Soil Till Res 133:40-48

Zaher H, Caron J, Ouaki B (2005) Modeling aggregate internal pressure evolution following immersion to quantify mechanisms of structural stability. Soil Sci Soc Am J 69:1–12

Figure 1

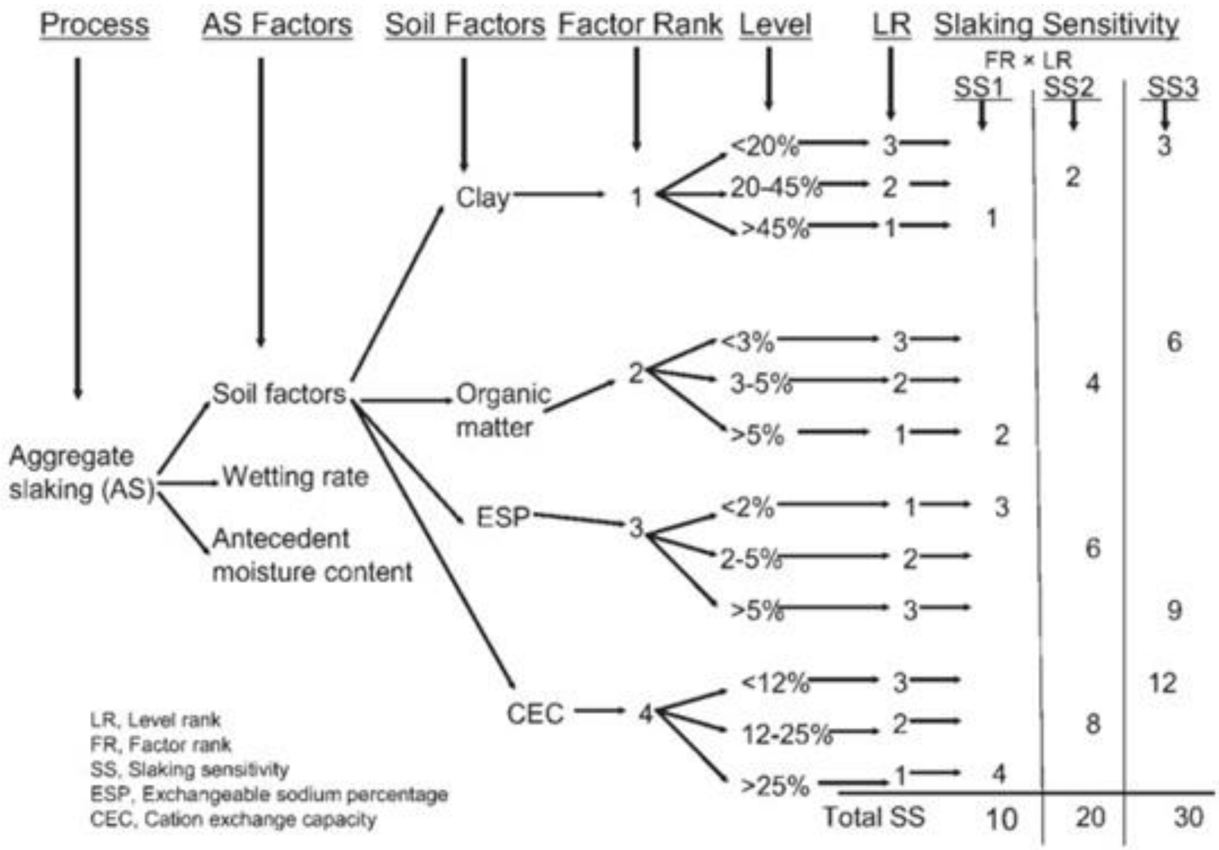

Fig. 1 Slaking Sensitivity Ranking Framework. Source: Wuddivira et al. (2010)

Figure 2

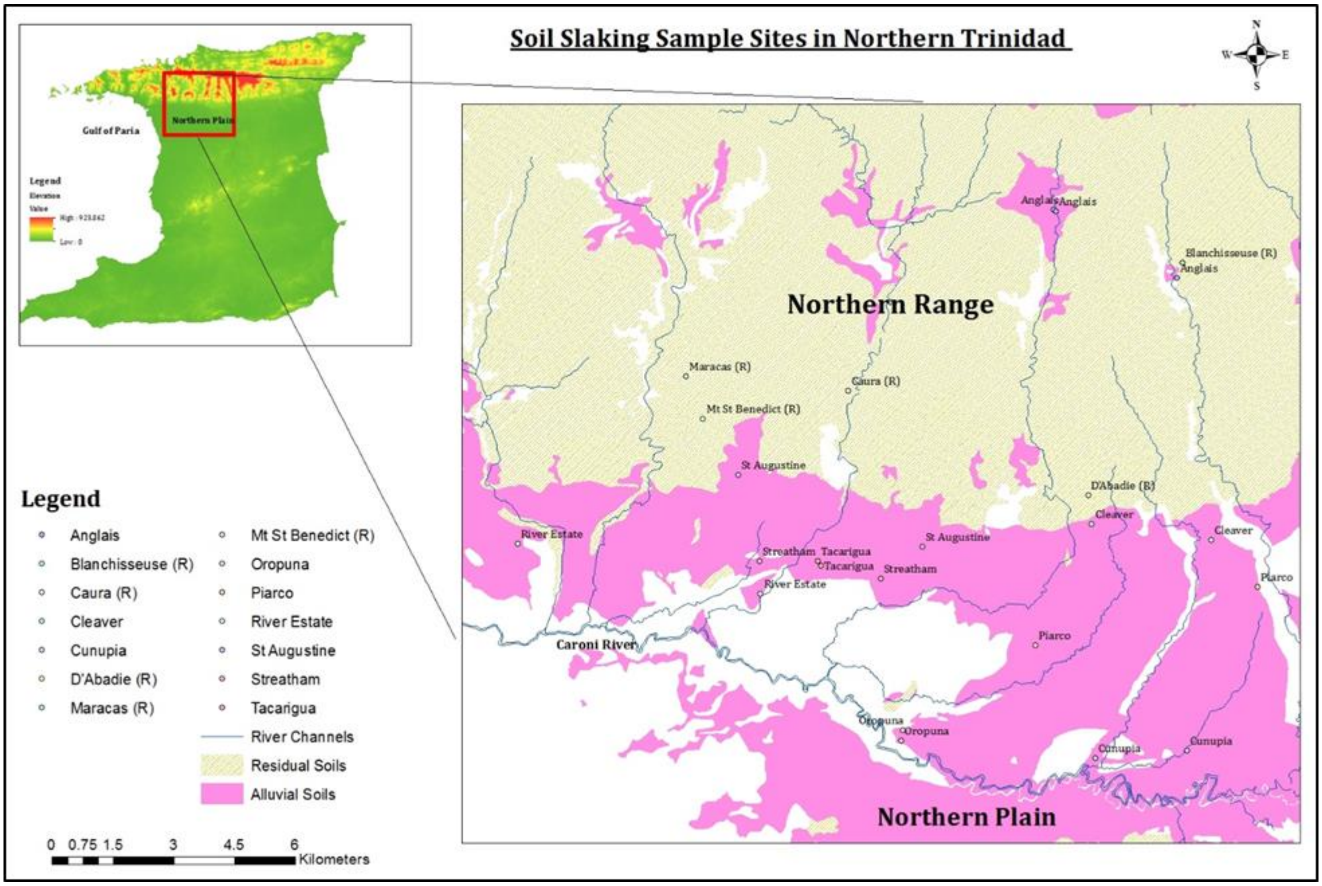

Fig. 2 Trinidad map (inset) showing sample locations of residual (R) and alluvial soils in Northern Trinidad

Figure 3

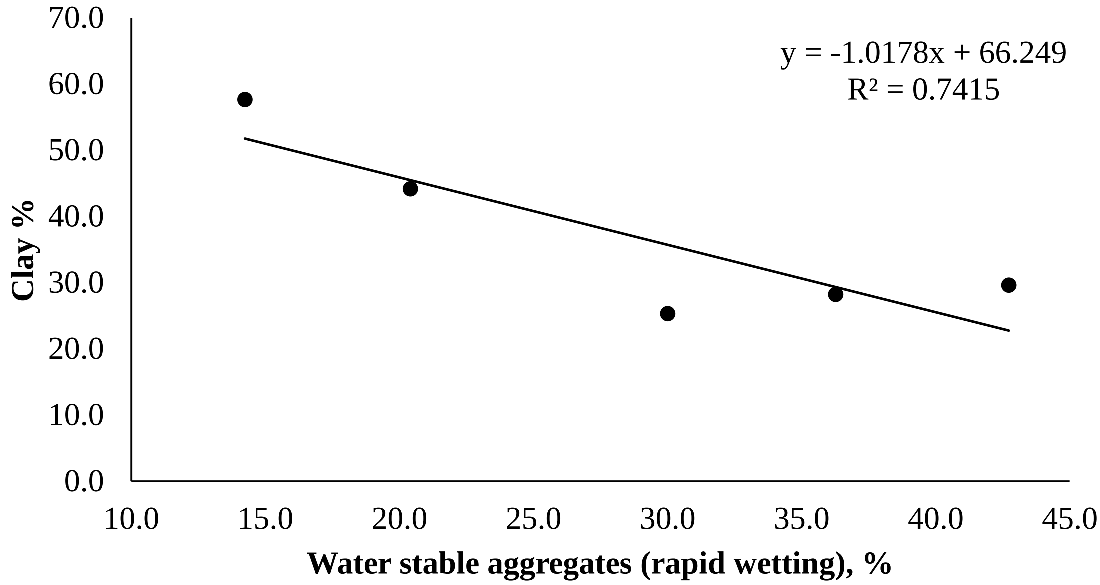

Fig. 3 Clay percentage vs Water stable aggregates by rapid wetting percentage

Figure 4

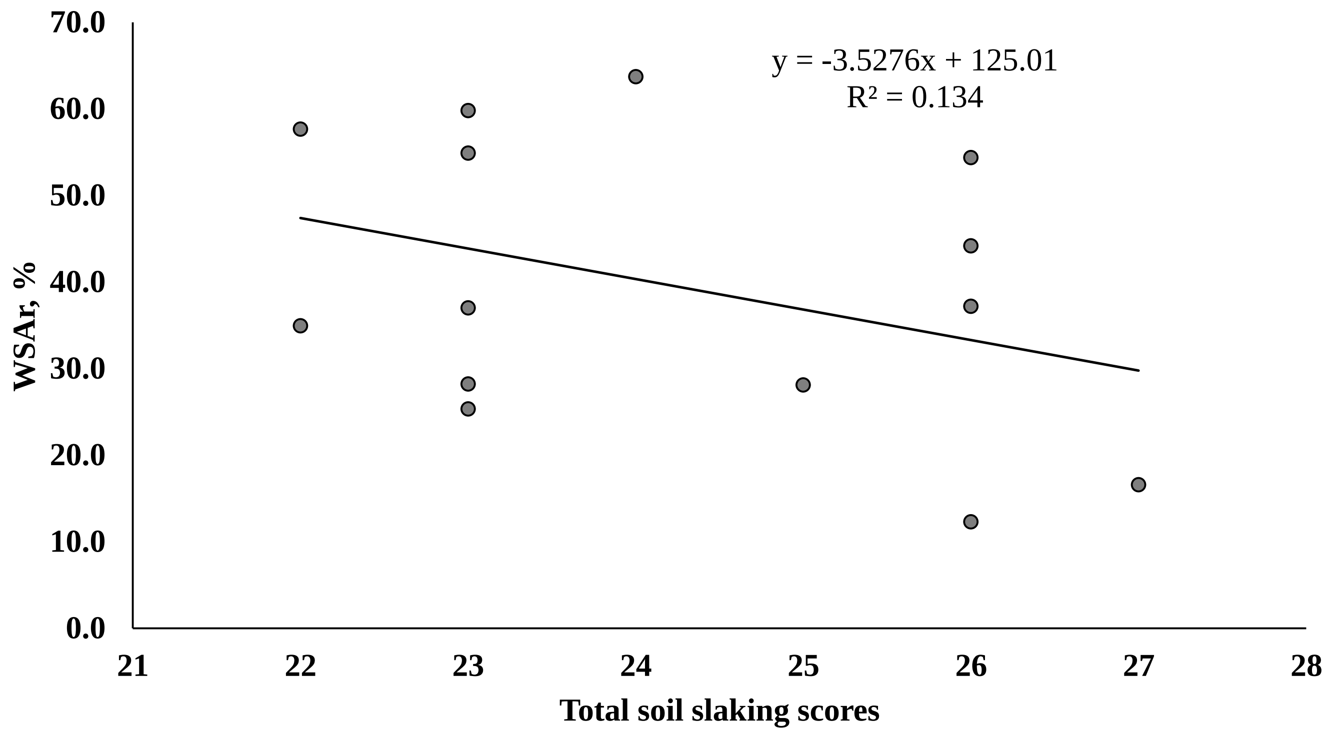

Fig. 4 Water stable aggregates under rapid wetting vs total slaking sensitivity scores for the 14 soils

Table 1 Soils and their USDA taxonomic descriptions

Physiographic zone		Soil	Subgroup	Family (Isohyperthermic)	Lithology
Northern Basin	Soils of the Alluvial plains and valleys	Cunupia (A)	Aquic Hapludalfs	Very-fine, mixed, acid	Silty clay, alluvium
		Tacarigua (A)	Dystric Fluventic Eutrudepts	Coarse-loamy, micaceous	Micaceous loam
		River Estate (A)	Dystric Fluventic Eutrudepts	Fine-loamy, micaceous	Mica phyllite sand
	Soils of the Terrace	St Augustine (A)	Aquic Hapludalfs	Clayey, Kaolinitic	Micaceous
		Piarco (A)	Typic Kanhaplaquults	Clayey, Kaolinitic	Sand and clay
		Cleaver (A)	Ombroaquic Kandiudults	Clayey, Kaolinitic	Loamy, hill wash
		Streatham (A)	Typic Plinthudults	Clayey, Kaolinitic	Schistose detritus
		Anglais (A)	Aquic Hapludults	Clayey, Kaolinitic	Mica, phyllite, quartze, sandstone
		Oropuna (A)	Typic Endoaquepts	Fine, Kaolinitic, Non-acidic	Clay
Northern Range	Upland soils	Mt St Benedict (R)	Unclassified	Micaceous, schist,	Micaceous, phyllite, Limestone
		Maracas (R)			
		Blanchisseuse (R)			
		D'Abadie (R)			
		Caura (R)			

Table 2 Physical and chemical properties of the soils

Soil	Texture	WSAr	PSc	Sand	Silt	Clay	Organic matter	ESP	CEC	pH
							%		cmol/kg	
Mt St Benedict (R)	Loam	57.7	11.8	48.7	37.1	14.2	4.4	1.1	4.4	7.0
River Estate (A)	Loam	16.6	0.6	48.0	37.6	14.4	0.7	3.7	2.3	6.9
Cleaver (A)	Loam	63.7	13.2	51.2	31.6	17.2	1.7	2.0	1.6	4.7
Maracas (R)	Loam	44.2	11.7	50.8	28.8	20.4	0.4	3.1	2.5	5.9
Tacarigua (A)	Silt Loam	37.2	4.1	21.5	56.1	22.4	0.5	3.0	2.8	7.5
Piarco (A)	Loam	37.0	4.5	38.3	38.5	23.2	0.9	1.1	2.5	4.7
Anglais (A)	Silt Loam	59.8	10	25.4	50.7	23.9	0.9	0.7	2.8	4.7
St Augustine (A)	Loam	54.4	7.4	47.3	28.1	24.5	0.8	3.0	1.7	5.5
Blanchisseuse (R)	Clay Loam	25.3	2.6	25.3	44.7	30.0	0.7	1.7	2.8	8.3
Streatham (A)	Silty Clay Loam	12.3	0.62	16.6	51.3	32.1	1.0	4.9	2.7	7.0
D'Abadie (R)	Silty Clay Loam	28.2	4.8	16.6	47.1	36.3	1.6	3.5	2.8	4.8
Caura (R)	Silt Clay	29.6	2.4	16.0	41.3	42.7	0.9	2.5	1.0	4.9
Cunupia (A)	Silty Clay	28.1	7.9	2.5	47.9	49.6	0.9	0.8	8.0	5.5
Oropuna (A)	Clay	34.9	1.7	9.0	22.8	68.2	1.8	1.0	9.5	5.3

(A) Alluvial soils. *(R)* Residual soils. *WSAr* water stable aggregates under rapid wetting. PSC percolation stability corrected ESP exchangeable sodium percentage. CEC cation exchange capacity

Table 3 Regression equations in the form of Y= a + b X and correlation coefficient (r) of the relationship between water stable aggregates under rapid wetting (WSAr) and (PSc) vs selected soil properties for soils grouped based on parent material origin and land cover

Soil Groups	X	WSAr %			PSc mm/10min		
		a	b	r^2	a	b	r^2
14 Soil Series	Clay %	-0.3738	48.981	0.12	-0.1192	9.5197	0.17
	OM %	5.9732	30.487	0.14	1.5221	4.0912	0.12
	CEC %	-0.7961	40.475	0.01	-0.1446	6.4398	0.01
	ESP %	-6.263	52.079	0.25	-1.3445	9.0195	0.16
9 Alluvial Soils	Clay %	-0.2365	45.464	0.05	-0.626	7.473	0.06
	OM %	11.453	26.843	0.07	2.2356	3.2973	0.05
	CEC %	-1.6247	44.342	0.06	-0.3169	6.7512	0.04
	ESP %	-6.2048	52.104	0.25	-1.4842	8.8782	0.25
5 Residual/Forest Soils	Clay %	-1.0178	66.249	0.74	-0.3658	17.171	0.79*
	OM %	6.0652	27.287	0.52	1.3888	4.4352	0.23
	CEC %	7.8029	16.131	0.46	2.5098	-0.0535	0.39
	ESP %	-6.4809	52.314	0.22	-0.8455	8.6575	0.03
5 Agriculture Soils	Clay %	3.6235	-37.621	0.78*	0.7078	-10.036	0.68
	OM %	0.004	0.5911	0.18	10.664	-2.711	0.23
	CEC %	-0.0001	2.4221	0.00	0.6671	3.7076	0.01
	ESP %	-0.046	4.1786	0.35	-1.8093	9.4669	0.45
4 Grasslands Soils	Clay %	0.392	55.386	0.15	-0.1537	12.272	0.33
	OM %	0.0146	0.8263	0.48	2.4389	2.6023	0.04
	CEC %	-0.0478	7.1136	0.07	-0.5584	8.8998	0.14
	ESP %	-0.0416	3.6143	0.23	-1.2622	8.5926	0.16

*P<0.05; WSAr is Water stable aggregates (rapid wetting); PSc Percolation stability (sand corrected); OM Organic matter; CEC Cation exchange capacity; ESP Exchangeable sodium percentage

Table 4 Soils slaking sensitivity (SS) score for individual factors, total SS score and water stable aggregates under rapid wetting (WSAr) for the 14 soils

Soil	SS Score (FR x LR) for individual factors				Total SS Score	WSAr %
	OM	Clay	ESP	CEC		
Mt St Benedict (R)	4	3	3	12	22	57.7
River Estate (A)	6	3	6	12	27	16.6
Cleaver (A)	6	3	3	12	24	63.7
Maracas (R)	6	2	6	12	26	44.2
Tacarigua (A)	6	2	6	12	26	37.2
Piarco (A)	6	2	3	12	23	37.0
Anglais (A)	6	2	3	12	23	59.8
St Augustine (A)	6	2	6	12	26	54.4
Blanchisseuse (R)	6	2	3	12	23	25.3
Streatham (A)	6	2	6	12	26	12.3
D'Abadie (R)	6	2	3	12	23	28.2
Caura (R)	6	2	3	12	23	54.9
Cunupia (A)	6	1	6	12	25	28.1
Oropuna (A)	6	1	3	12	22	34.9

FR factor rank. LR level rank